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SPECIFICATION OF RADAR ERROR FOR ADCOM RADARS WITH ADAPTIVE MOD--ETC(U)

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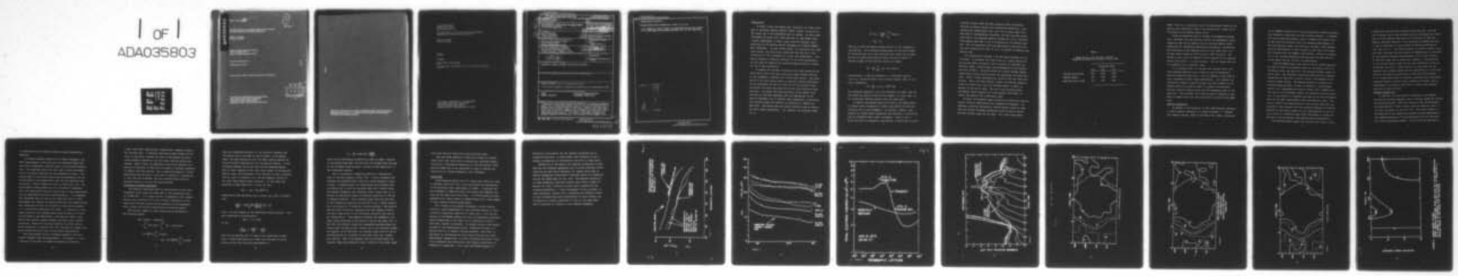

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SPECIFICATION OF RADAR ERROR FOR ADCOM RADARS WITH ADAPTIVE MODELING

Delia D. Dulong
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Scientific Report No. 1

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Examination of the space and time variability of the expected ionospheric range error at ADCOM radars suggests that the day to day variability may be reduced using an adaptive modeling technique. A model of the range error correction for the entire field of view is specified by range error measurements along the path of a TRANSIT satellite and/or along the path to any synchronous beacon satellite. For targets in the upper ionosphere the residual range error from the day to day variability with respect to the

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monthly median may be reduced by a factor of 4 to 10.

For targets at F-region eights the improvement may be only a factor of 2 if the height and thickness parameters are not also specified.

INTRODUCTION

In order to meet the design goal accuracies for radar metric data at Aerospace Defense Command (ADCOM) radars, the errors at the target due to the ionosphere must be removed. An AFGL study (Klobuchar and Allen 1976) concluded that at some ADCOM radars a useful improvement in metric error could be obtained from a prediction of the monthly median ionosphere by standard AWSGWC/AFGL techniques. At other ADCOM radars, and especially for those under design, the bias errors associated with the day to day variability of the ionosphere are larger than ADCOM goals. This report examines a technique designed to use field measurements in real time for adapting the predicted median values to reduce the day to day variability.

To examine the concept of making a real time correction for range errors that arise when radio waves pass through portions of the ionosphere, consider any VHF/UHF radar system. The group delay of the radio waves, which is the basic system measurement, can be considered the sum of a part due to the distance along the actual wave path and a part due to the free electrons along that path. By making the simplifications to the steady state solutions of the wave equations that are appropriate to the earth's ionosphere and to VHF/UHF radio frequencies, a Euclidean line between source and receiver is sufficient to define the wave path. This means that the angular deviation may be ignored for first order calculations. For instance, the measured range (R) is

$$R = R_o + \frac{2\pi e^2}{mew^2} \int_{s_1}^{s_2} Ne(s)ds$$

$$= R_o + \delta R$$

where R_o is the free space distance and δR is the ionospheric contribution. δR is directly proportional to the total number of electronds per unit cross sectional area along the ray path, and may be calculated piecewise along the line of sight (θ) through a model of the electron density vs height.

$$\delta R = \frac{k}{f^2} \sum_{h=h_1}^{h_2} \sec \theta(h) \; Ne(h) \Delta h$$

Alternatively, it may be estimated as a fractional portion ($\rho(h_1, h_2)$ of the vertical total electron content (TEC) of the entire ionosphere

$$\delta R = \frac{k}{f^2} \rho(h_1,h_2) \; \overline{\sec \theta} \; TEC$$

The frequency dispersion, the time dependence of phase, and the correction for angle of arrival also depend, to first order, on the integrated electron content along the slant path.

In theory, any system could be devised to use measurements at several radio frequencies to make a correction for the contribution due to the ionosphere. In practice, however, most systems use single radio frequencies and therefore, a correction must be estimated from a model ionosphere. There is now a world data pool of systematic observations of equivalent vertical

electron content which has been measured using the Faraday rotation of beacon signals from synchronous satellites. This archive data demonstrates that, over the latitude range from Hong Kong to Narssarssuaq, Greenland, and over the most recent solar cycle, the expected monthly variability (r.m.s. deviation from monthly mean TEC) is 20 to 25 percent of the monthly mean TEC. This is consistent with the observations from world data that the variability of foF2 is 10 to 12 percent of monthly mean daytime foF2.

For perspective, consider a 425 MHz radar situated at mid-latitudes. To estimate the range error for a space vehicle orbiting well above the peak of the F2 region, we reference the Hamilton, Mass., archive data from measurements of the Faraday rotation of ATS-3. At mid-latitude the largest monthly median values occur during solar maximum, the equinoxes, and local daytime. Table 1 gives representative values of TEC for these conditions. Note, the range between largest and smallest observations at a given hour, over the calendar month, is about 75 percent of the hourly mean. The day to day variation about the median values expected for solar maximum (1979-1981) is larger than desired for a precision radar.

To model the expected range correction a profile of electron density could be constructed from ionospheric parameters. By choosing a form for the profile, monthly median values of foF2, hmF2 and various thickness parameters could be used to derive electron content along the ray path. For a very good median

TABLE 1

Range Errors, Feet One Way, 425 MHz
Expected for March 1978-1980 at $42^{\circ}N$, $70^{\circ}W$

	Elevation Angle		
	85°	22°	0°
Largest Daily Value	649	1364	2013
Monthly Median	485	1019	1505
Smallest Daily Value	321	675	996

model, the r.m.s. variability about the predictions should be the same as the variability found in the archive data - about 20 to 25 percent of the monthly median value.

Using the numerical maps of medians of ionospheric parameters, available from the National Oceanic and Atmospheric Administration, and the Air Weather Service electron density model tested against independent observations by Mulkern, estimations have been made of the expected values of the range error for a 425 MHz radar located at 42°N latitude, 70°W longitude. The residual range error is assumed to be 25 percent of the expected median range error, a 1 sigma estimate. This is larger than can be acceptable for a precision radar.

It is proposed that, to overcome the residual error from using expected medians, such a model be used to establish a baseline prediction and that it then be adapted in real time by local ionospheric and/or radar measurements. For instance the differential doppler observed between two radio beacons on the TRANSIT satellites could be used to estimate the equivalent vertical electron content along the sub-ionospheric path of the satellite. This estimate could then be used to specify an area model of range error over the entire field of view of the ADCOM radar.

SPATIAL VARIABILITY

An example of the potential of this specification technique to remove spatial variability is shown in Figure 1. Differential Doppler records, taken at Millstone Hill, Mass., using one

of the TRANSIT satellites of the Navy Navigation Satellite System, were reduced to equivalent vertical electron content. A standard Air Force prediction program, used to estimate the median value of TEC along the satellite path, and separate measurements of TEC from Hamilton, Mass. and Goose Bay, Labrador, using Faraday rotation measurements of ATS-3 signals at the time of the pass, were compared with the TRANSIT observations. There is a general fit of the latitude gradients along the path for both the predicted median and the two sets of observations.

From the TRANSIT pass, the value of TEC at closest approach was used to scale the predicted median at this point, and this correction factor was applied to the predicted median along the entire path. The resultant normalized prediction has a spatial variability of less than 5 percent within a few degrees of the central scaling region. The maximum deviation increases with distance along the path, to about 10 percent at the extremes. Figure 2 is a representative daytime sample with a TRANSIT pass from each of five different months, the selection criteria being that it fall within ±0.5 degrees longitude of the sub-ionospheric point of the ATS-3 measurements made from Hamilton, Mass. The initial results for specification of the daytime ionosphere are consistent, and indicate that the proposed technique of adaptive modeling of the median range error by normalization to the central region of a satellite pass track can produce a tenfold reduction of the variability from monthly median observations.

The expected median range error during night hours is about

a magnitude less than that expected during the day. Although the 30 percent day to day variability about the median for nighttime is only slightly worse than the 20 percent for daytime, sharply localized features in the nighttime ionosphere may make it just as necessary to use an adaptive modeling technique at that time (Fig. 3). The steep gradient of electron content found over small latitude intervals along the TRANSIT path is confirmed by the gradient measured simultaneously with the ATS-3 beacon at Hamilton, Mass. and at Goose Bay, Labrador. The prediction of the monthly median, which has not been normalized to the observations, has only a slight gradient at this time, but the absolute error between prediction and observation is of the same order as the absolute daytime error using the scaled median. If it is determined that the observed gradients are a consistent nighttime feature, scaling could introduce new errors, and an improvement in prediction would have to result from improved modeling of these features.

TEMPORAL VARIABILITY

In parallel with the spatial variability, the temporal variability has been examined, using a similar scheme for scaling the predected median. The local values of TEC are determined from measurements of ATS-3 signals taken at Hamilton, Mass. in 15-minute intervals for the year 1972. The effectiveness of the predicted 10-day median was examined through comparison of the standard deviation of the observations with the rms deviation from the predicted median. Since errors are equivalent,

it indicates that the observed median is being successfully modelled.

To simulate adaptive updating of a model ionosphere, the ATS-3 measurements in TEC units and the predicted median TEC were used to determine a scaling factor at each hourly observation. The resultant factor was then used to scale the prediction at 15 minute intervals for the succeeding 12 hours. The monthly mean of this scaled prediction was determined, and the rms deviation of the observations from the new prediction was calculated. Figure 4 shows the error, in TEC units, for: the hourly-based 12-hour predictions for the month of September, 1972; the observations from the monthly mean of the observations; and the observations from the predicted median. It is apparent that throughout most of the day and nighttime hours, a local measurement will improve the median prediction for several hours, with reductions in error of 50 percent or more still possible 2 or 3 hours after normalizing the model. A constraint in this scheme occurs in the pre-dawn period when the error for a prediction based on any measurement, including one taken in the period near sunrise, rapidly exceeds the error using a median prediction. Except for this brief period, the error using a scaled prediction is usually less than, and does not exceed, the median prediction error even 12 hours after normalization.

The effectiveness of this technique depends on the time interval between local TEC measurements. In Figures 5, 6, and 7 contours of rms error of predictions based on 30-minute,

1-hour, and 2-hour observations, respectively, summarize results for the year 1972. A 30-minute observation would reduce the rms error to less than 5 percent for most of the daytime and would rarely exceed 10 percent at any time other than the period near sunrise. After 1-hour, an observation would still provide a reduction in rms error to less than 10 percent in daytime, exceeding 20 percent only near sunrise. For a prediction based of a 2-hour observation the rms error is less than 15 percent for daytime and is less than the 25 percent rms error expected when using the predicted median in all but the sunrise period.

VARIABILITY OF MODEL PARAMETERS

The previous reductions apply to specification of the total ionospheric error along the slant path to the calibration vehicle (SLANT TEC). If a target vehicle is embedded in the ionized region, only a portion of the slant content contributes to the range error and that portion can be sensitive to the parameters used to model the vertical distribution of electron density.

The relative change in slant content can be estimated in the following manner:

$$
\begin{aligned}
\text{TEC} &= \text{Actual} - \text{Predicted} \\
&= \int_{s_1}^{s_2} N_1 P_1(s)\,ds - \int_{s_1}^{s_2} (N_O + \Delta N) P_O(s)\,ds \\
&= N_1 \overline{\sec \theta_1} \int_{h_1}^{h_2} P_1(h)\,dh \\
&\qquad - (N_O + \Delta N)\, \overline{\sec \theta_2} \int_{h_1}^{h_2} P_O(h)\,dh
\end{aligned}
$$

where the normalized profiles (P) are slightly different and the density (N) at the peak of the F2 region, in the median model, has been adjusted so that the model content matches the electron content observed with the calibration vehicle. If the difference between the actual hmF2 and the predicted median hmF2 is small compared to the local scale height of the electron density, then, the difference in the profiles is just a vertical shift of $P_o(h)$ to produce $P_1(h)$, and the geometric factors of the slant paths remain nearly identical. In that case, TEC maximizes at hmF2 where P(h) is unity, so that

$$\text{TEC} \approx (N_o + \Delta N)\, \overline{\sec\theta}\, \Delta h$$

Normalized to the equivalent slant content (N_c) used in calibration,

$$\frac{\Delta\text{TEC}}{\text{TEC}} \approx \frac{(N_o + \Delta N)\, \overline{\sec\theta_o}}{N_c\, \overline{\sec\theta_c}} \frac{\Delta h}{\tau} \approx \frac{\Delta h}{\tau}$$

where τ is the integral of the normalized vertical profile. Over most conditions at mid-latitudes,

$$\text{hmF2} < \tau \leq 2\ \text{hmF2}$$

so that

$$\frac{\Delta h}{2\ \text{hmF2}} \leq \frac{\Delta\text{TEC}}{\text{TEC}} < \frac{\Delta h}{\text{hmF2}}$$

From this we conclude that if there is an uncertainty in hmF2 alone, a worst case would be a target near the peak of the F2 region and the error would be approximated by

$$\Delta R \approx \frac{k}{f^2} \text{ SLANT TEC } \frac{\Delta hmF2}{hmF2}$$

Since the rms percentage variability of hmF2 is about 7 percent of the monthly mean hmF2, the rms error for targets near the peak of the F2 region would be about 7 percent of the range error to the calibration vehicle.

Fig. 8 illustrates a comparison made for a hypothetical radar at 425 MHz located at 42°N, 70°W. A model ionosphere was produced for expected median conditions during daytime at solar maximum. A separate model was established which differed from the median only in that the parameter NmF2 was 7 percent lower. This second ionosphere was integrated along a slant path to represent an observation using a calibration satellite at 1000 km, 22 degrees elevation. This "observed range error was 563 feet at the calibration satellite and was 838 ft for a target vehicle near the horizon at 4° elevation, 1000 km altitude. The electron density within the median ionosphere was then adapted to match the slant range error to the calibration satellite with that of the "observation". This adapted ionosphere was compared to all other target positions in the field of view of the radar, Fig. 8. Note that the residual range error approaches maximum values for targets near the peak of the F region and at low elevation angles: for example, at 4° elevation, the residual range error at 300 km altitude was 68 ft, 8 percent of the slant error for a target near 1000 km. This is as expected from the analysis where the residual range error should be about 7 percent of the total range

error that would be found along each particular path.

This one sigma departure of NfF2 alone leads to residual range errors that could not be tolerated for precision radars. In practice, simultaneous departures of foF2 and profile thickness with NmF2 have to be considered in order to specify the range error for targets embedded in the ionosphere.

CONCLUSIONS

Using expected median values of range error alone will lead to residual errors on a day to day basis which are unacceptable to the precision radar requirements of ADCOM. A technique has been proposed to adaptively model the spatial and temporal variation of the range error correction. Its effectiveness has been examined with a small sample of TRANSIT passes and a large sample of total electron content measurements.

For a target in the topside ionosphere, initial results indicate a local measurement of total electron content is sufficient for a significant reduction of range error. From the comparison of the TRANSIT passes with their corresponding normalized median predictions it was shown that a reduction in error to less than 5 percent is possible, in daytime, within a few degrees latitude of the normalization point, increasing to about a 10 percent error at 15 degrees latitude distance. This error is equivalent to the daytime rms error using 30-minute and 1-hour observations, respectively, to scale the median prediction, which is an indication that mean spatial and temporal variations are comparable in magnitude. Also, since the TRANSIT passes are

effectively north-south, and the temporal variations can be considered east-west, it would appear that direction is not a primary consideration in determining variation on a mean basis.

Examination of the spatial and temporal variability of foF2, hmF2 and the thickness parameters used to derive electron content along the ray path may be necessary for systems which wish to specify propagation corrections to vehicles within the ionsophere such as the ADCOM radar at Otis, AFB. The expected variability of these parameters from their monthly mean values is about 10 percent for foF2, 7 percent for hmax, and 15 percent for the thickness parameters. A local measurement of one or several of these parameters, coupled with a specification technique similar to that discussed here using measurements of total content, may be required to achieve reductions in error to the same order that is possible for vehicles in the topside ionosphere.

Fig 1

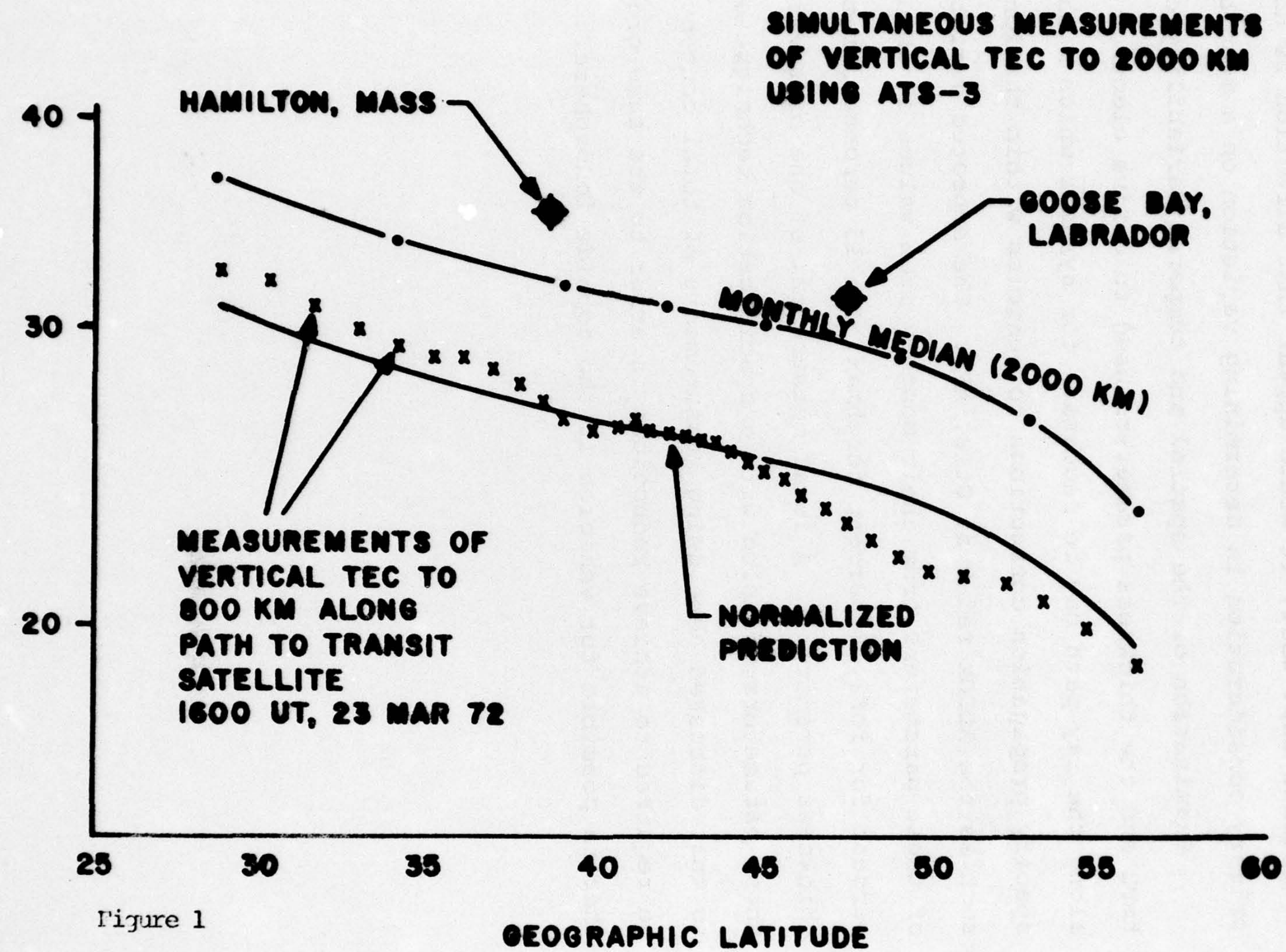


Figure 1

Fig 2

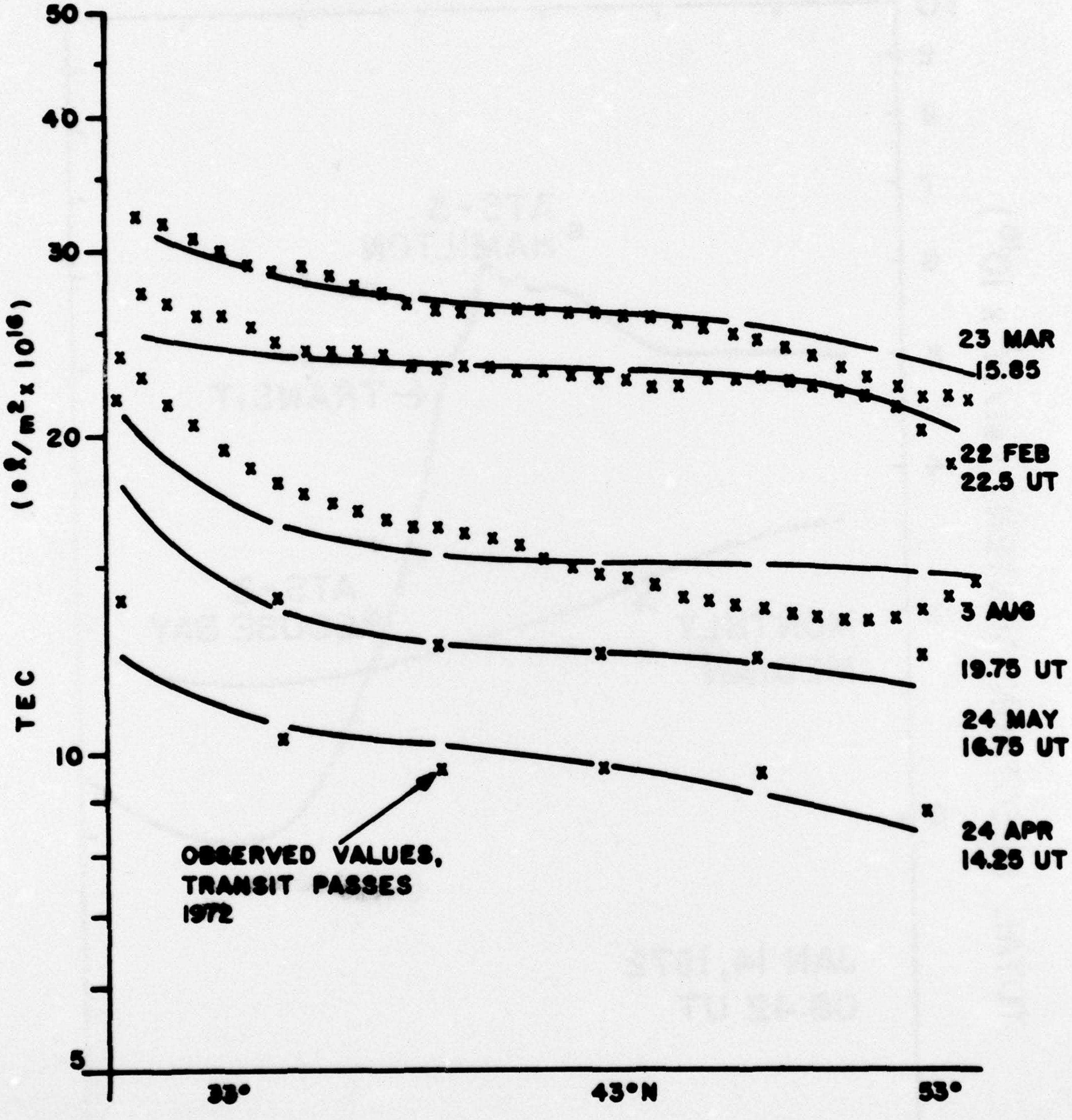


Figure 2

Fig 3

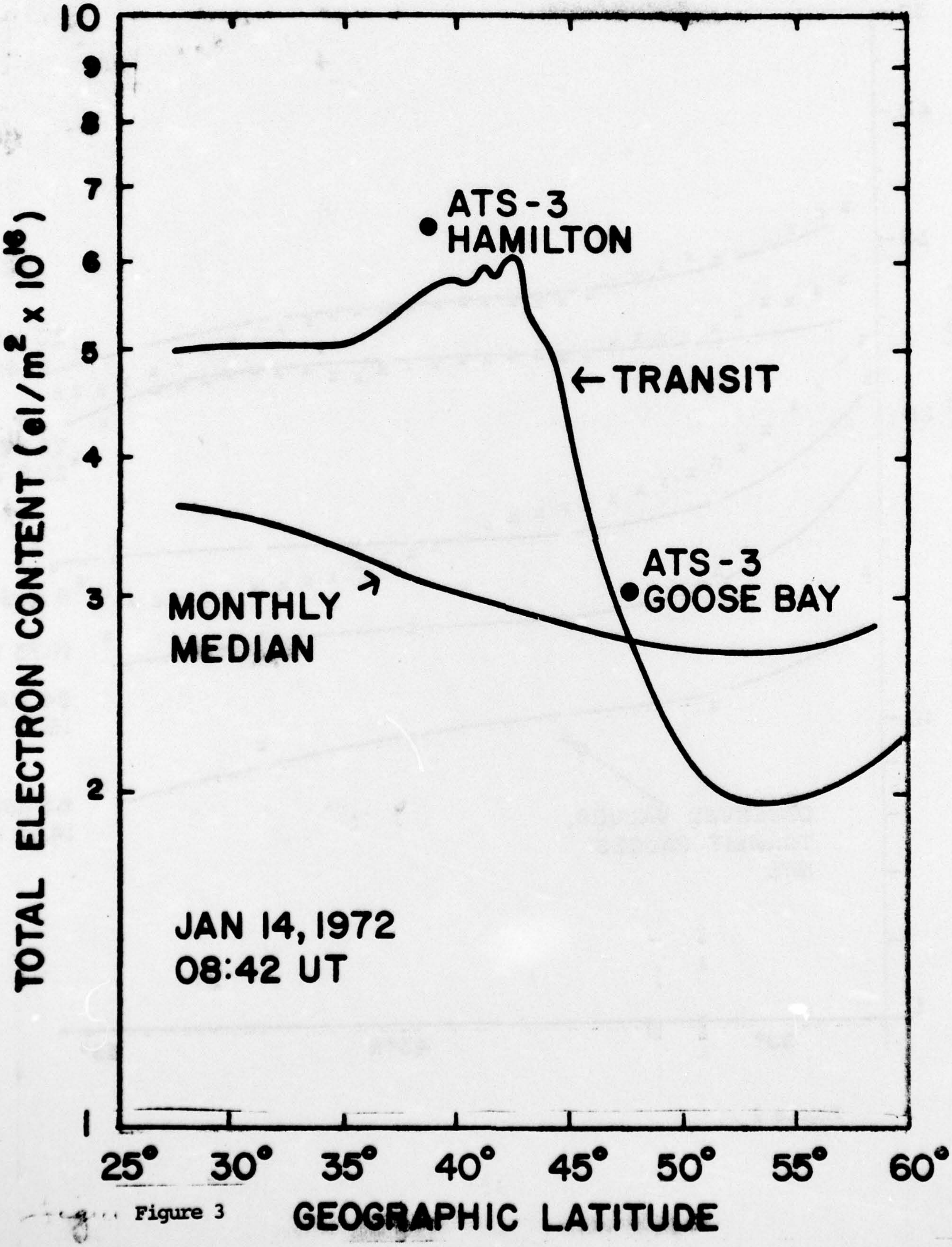


Figure 3

4

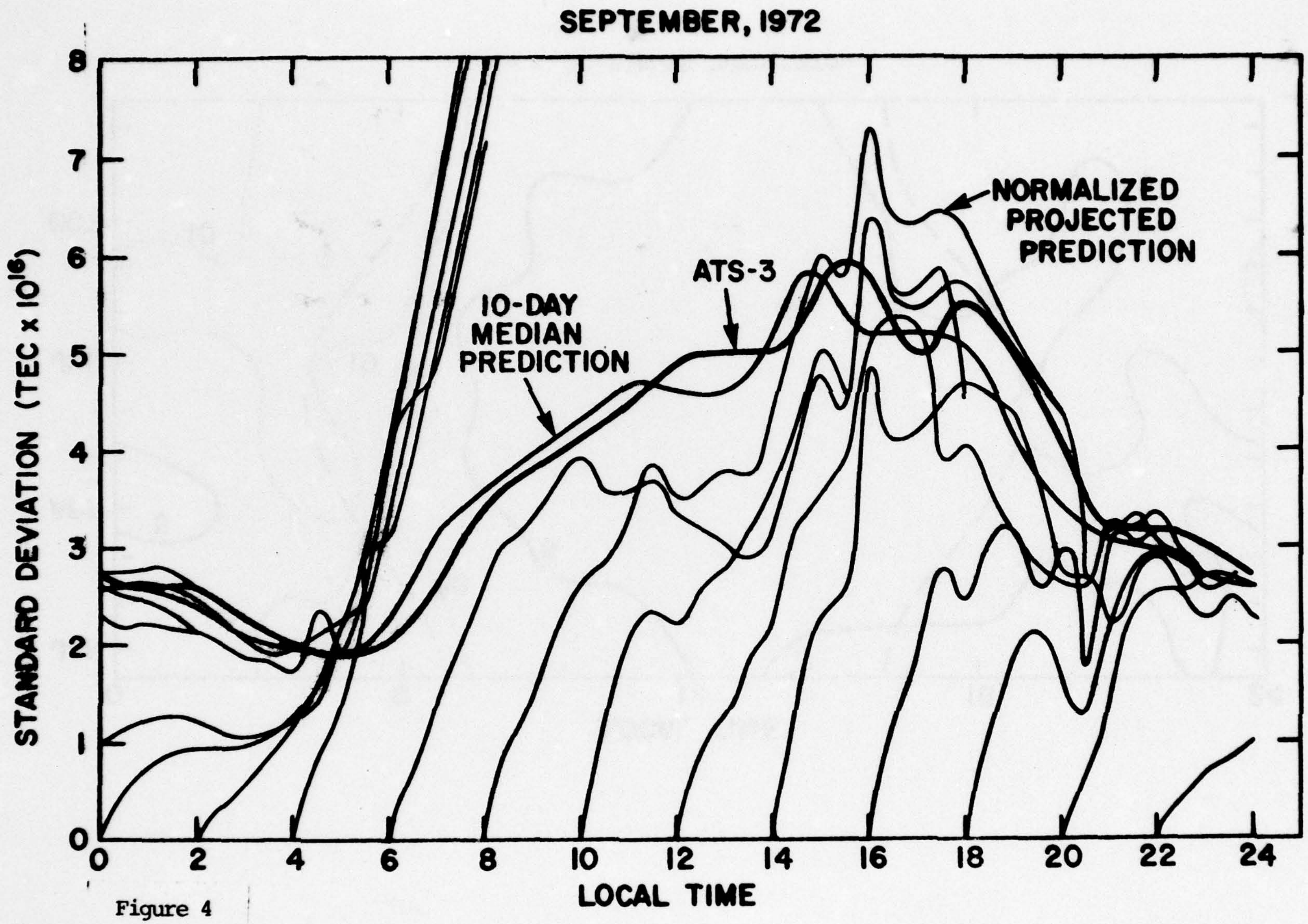

SEPTEMBER, 1972
NORMALIZED
PROJECTED
PREDICTION
ATS-3
10-DAY
MEDIAN
PREDICTION
STANDARD DEVIATION (TEC x 10^16)
LOCAL TIME
0
2
4
6
8
10
12
14
16
18
20
22
24
0
1
2
3
4
5
6
7
8

Figure 4

30 min prediction

5

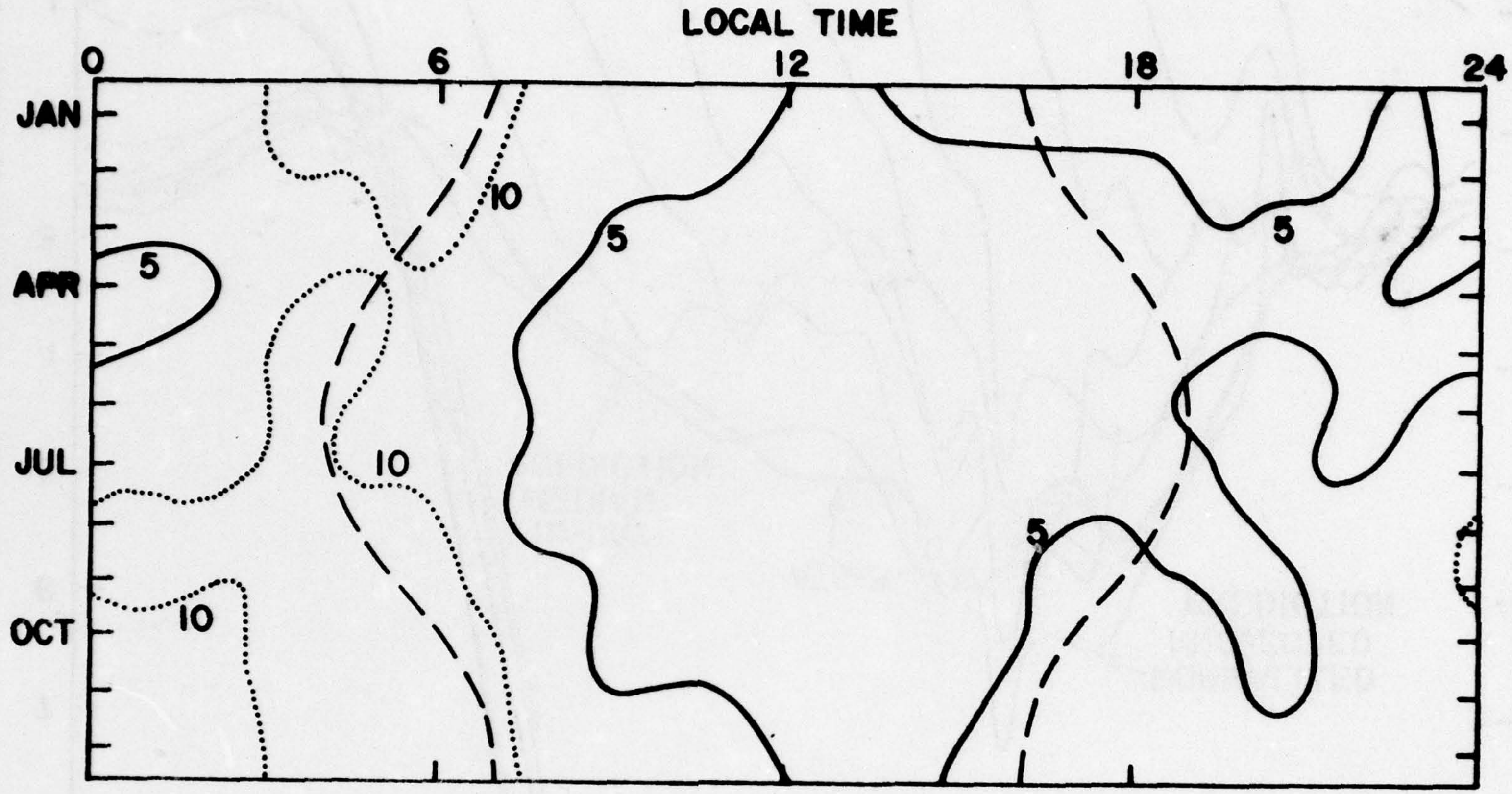
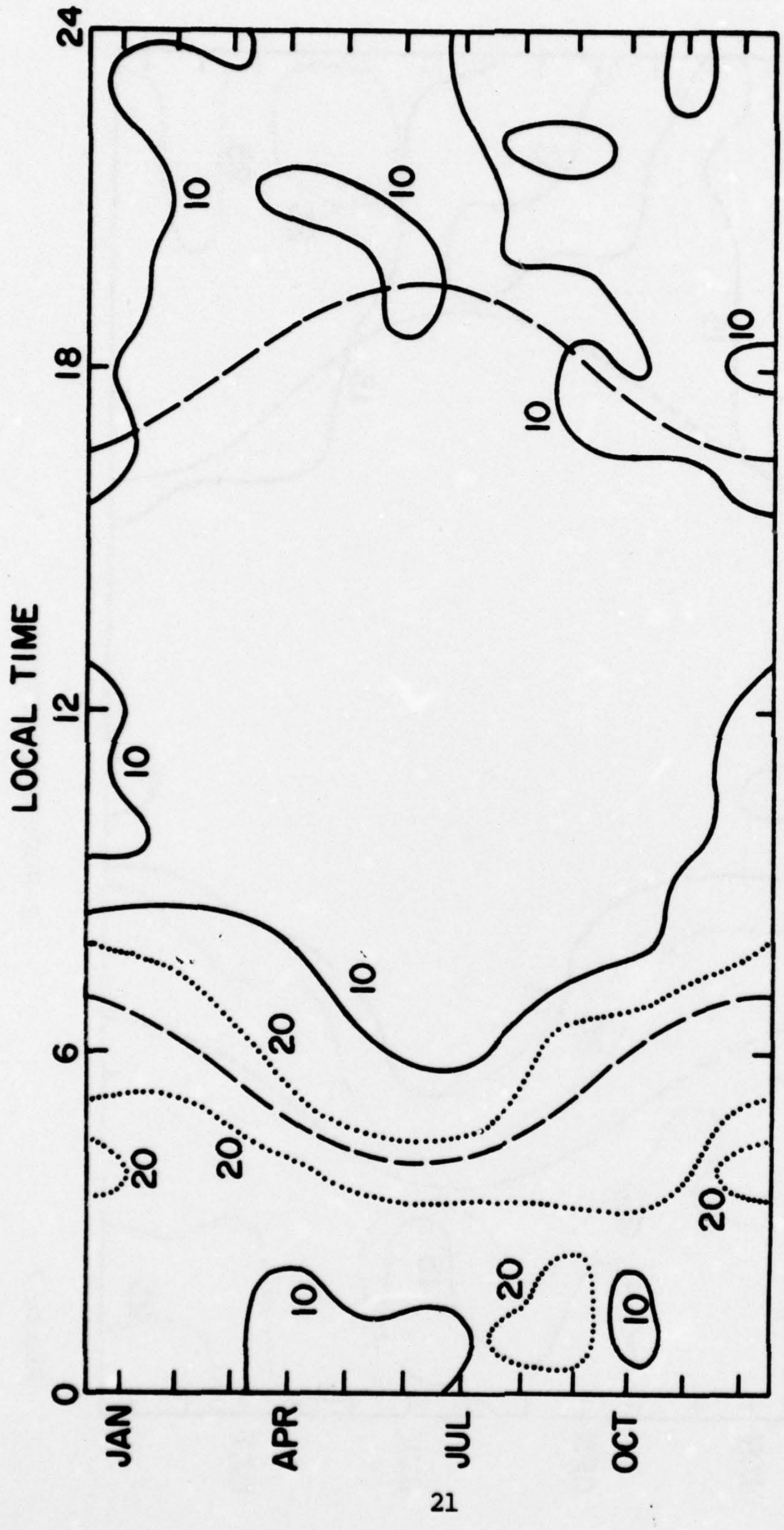


Figure 5 30-MINUTE PREDICTION



RMS PERCENTAGE ERROR
1 HOUR PREDICTION
SCALED 10-DAY MEDIAN
HAMILTON

Figure 6

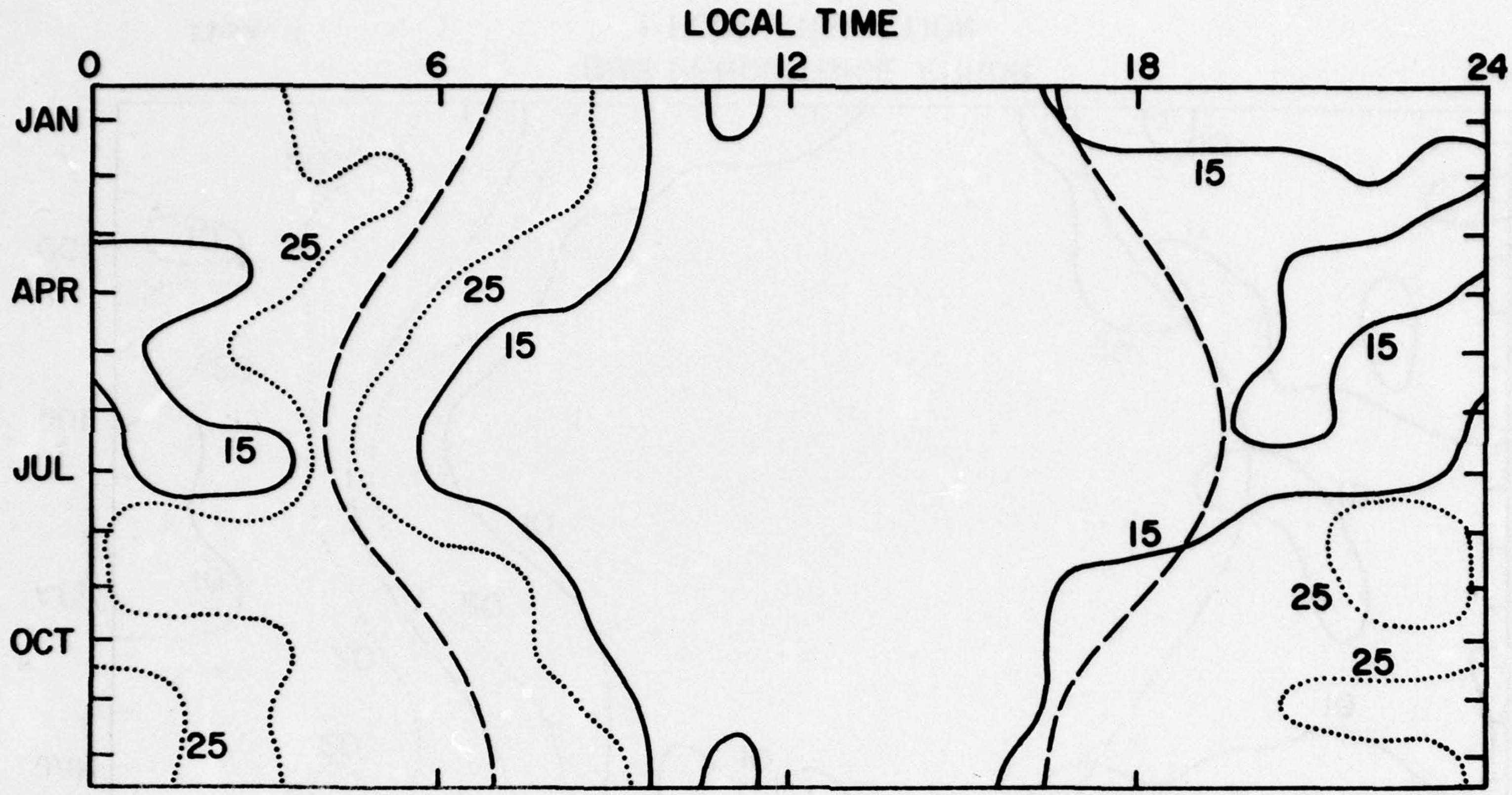


Figure 7

2-HOUR PREDICTION

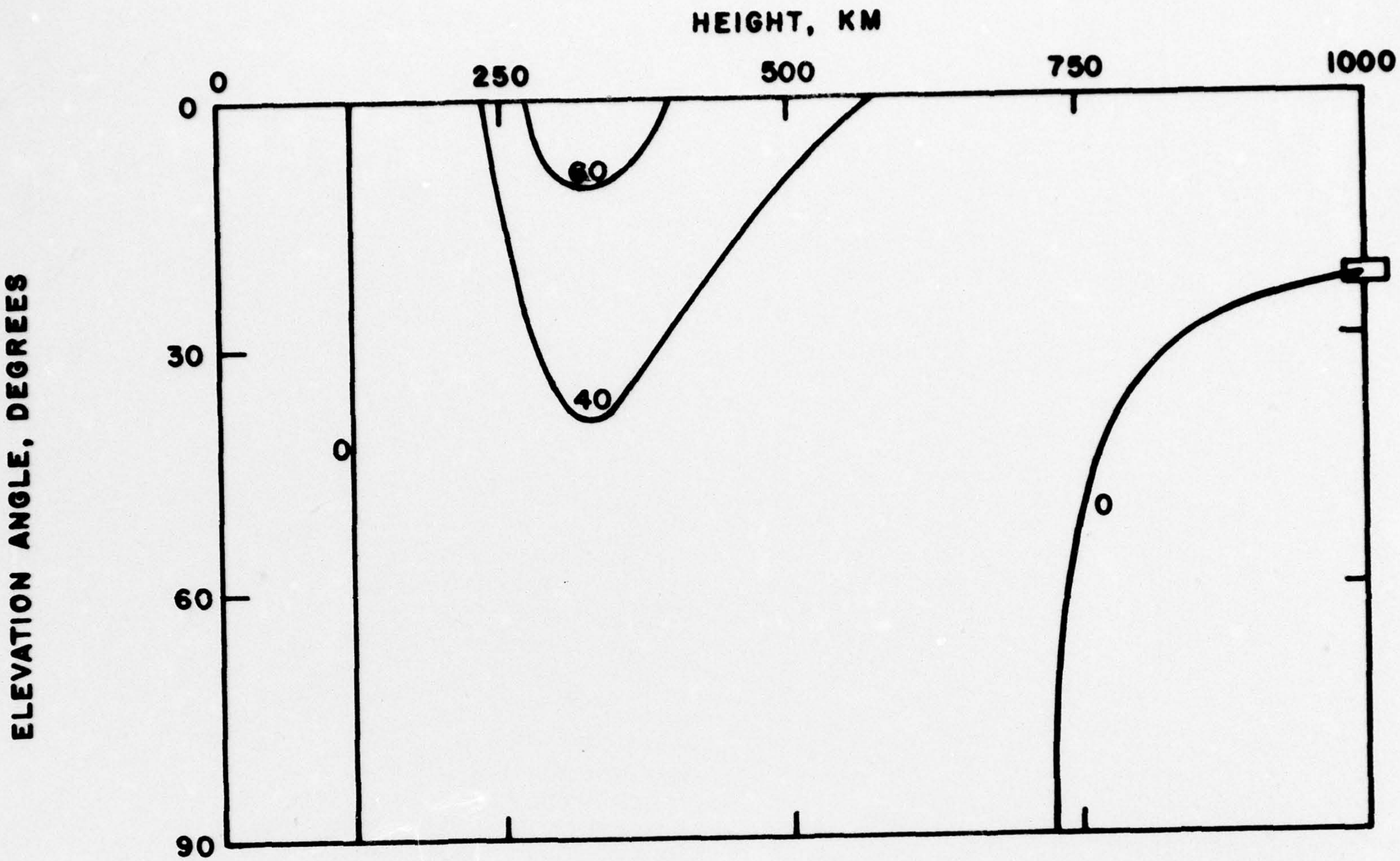


FIGURE 8 RANGE ERROR, IN FEET.
WORST MEDIAN CONDITIONS WHEN SPECIFIED BY A SLANT OBSERVATION TO A TARGET AT 22 DEGREES, 1000 KM ALTITUDE, IF THERE IS A 5 PERCENT ERROR IN THE HEIGHT OF THE F REGION.